Innovative research on flow instabilities in hydropower turbines for the integration of new renewable energy

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１． 研究課題

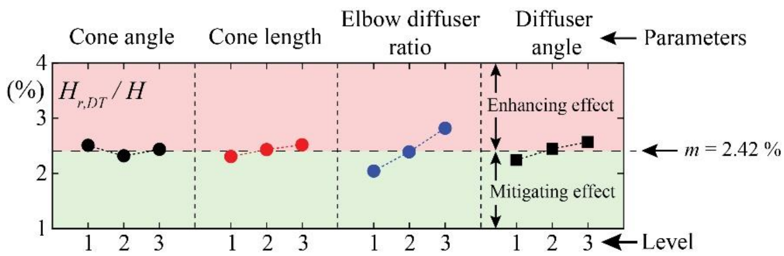
In the context of increasing electricity production by intermittent New and Renewable Energy (NRE) sources such as wind and solar, hydropower will play a crucial role in the power network by providing grid frequency control and balancing between electricity production and consumption. This, however, requires flexible operations of the hydropower units, notably the extension of their operating range to off-design conditions, where they are subject to dramatic flow instabilities putting at risk the system stability.

This research proposes to reach a better understanding of the physical mechanisms involved in draft tube flow instabilities and, in turn, to implement new optimized draft tube designs and flow control methods. An approach based on both fundamental and applied research is proposed. The fundamental physics of the turbine flow were investigated on simplified test-cases and the new gathered methodologies for the optimization of turbine design and flow controls are finally applied to an actual Francis turbine model. In addition, the physical mechanisms of self-excited cavitation flow phenomena are investigated on a reduced scale model of Francis turbines at both part-load and full-load conditions for further modelling and prediction of these types of instability in full-size hydropower stations. This may represent an important milestone towards the safe operating range extension and flexible operations of hydropower units to fulfill with the new requirements of the electrical power network.

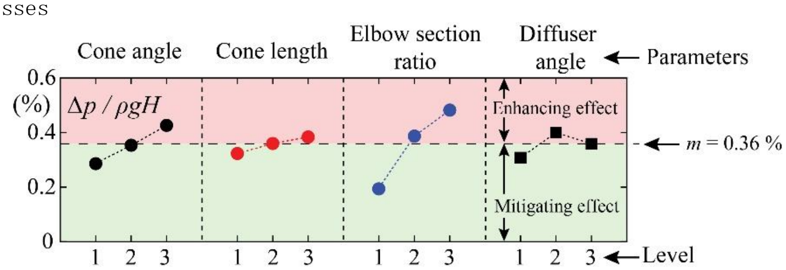
２． 主な研究成果

(1) Influence of the draft tube geometry on flow instabilities and energy losses analyzed by a Design-of-Experiments approach

The influence of the geometry of Francis turbine draft tube on pressure fluctuations and energy losses in off-design conditions was investigated by combining Design of Experiments and steady/unsteady numerical simulations of the draft tube internal flow. The test case is a 1.5 MW Francis turbine unit located in Japan which is required to operate continuously in off-design conditions, either with 40% (part load) or 100% (full load) of the design flow rate. Nine different draft tube geometries featuring a different set of geometrical parameters defined by Design of Experiments (DOE) are designed. For each of them, unsteady and steady simulations of the internal flow from guide vane to draft tube outlet are performed at part-load and full-load conditions, respectively. The influence of the draft tube geometry on the helical precessing vortex in part-load conditions was first investigated by identifying the vortex trajectory along the DT in each individual draft tube geometry. Furthermore, the influence of each geometrical parameter (including diffuser angle, cone length, cone angle) on the resulting pressure fluctuations and energy losses in the draft tube was assessed by applying an Analysis of Mean (ANOM) to the numerical results. The results are given in Figure 1 for the part-load conditions. This original approach enables the definition of a set of geometrical parameters enabling the mitigation of pressure fluctuations occurring in part-load conditions as well as the energy losses in both full-load and part-load conditions while maintaining the requested pressure recovery. The final draft tube design is finally validated by unsteady CFD simulations. The results from CFD simulations of the final design are compared with the energy losses and pressure fluctuations amplitude estimated by using the ANOM results, and deviations lower than 10% are observed. The final design is being tested in laboratory by reduced scale model tests before installation on the full-size prototype machine.



(a) Draft tube losses



(b) Amplitude of the pressure fluctuations at the draft tube inlet

Figure 1 Results of the DOE-ANOM for the draft tube losses and pressure fluctuations amplitude in part load conditions

(2) Dynamic behaviour of an elliptical cavitation vortex in Francis turbines

Certain Francis turbines are subject to the occurrence of a self-excited cavitation vortex instability when operating in upper part-load (UPL) conditions, around 80% of the design value of the flow rate. This phenomenon is characterized by the occurrence of high-frequency (f_{UPL}) synchronous pressure fluctuations in the complete system and may be associated to the formation of an elliptical cross-section of the cavitation vortex that rotates around the vortex axis. This phenomenon has been investigated by performing high-speed visualizations with two cameras and pressure measurements along the draft tube on a reduced scale model of a Francis turbine in Waseda University.

By performing a spectral analysis of the vortex diameter evolution estimated from the high-speed videos, it was first confirmed that the occurrence of UPL instability is necessarily accompanied by the formation of an elliptical cross-section of the vortex. As the system enters self-excited unstable conditions, a transition from a circular to elliptical vortex shape is observed, the latter reaching its maximum during fully developed instability [3]. In addition, the analysis of the vortex diameter evolution along the draft tube during fully developed UPL instability revealed the behaviour of the cavitation vortex dynamics.

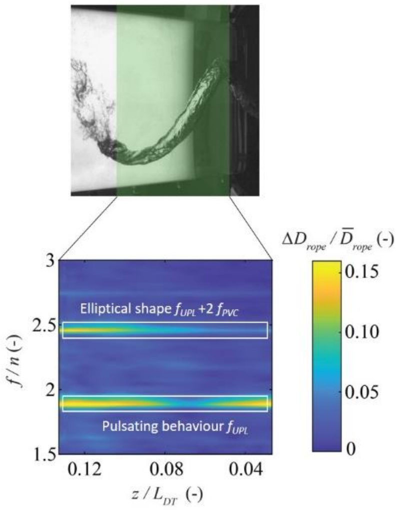


Figure 2 Spectral analysis of the cavitation vortex diameter evolution along the draft tube

By performing a cross-spectral density analysis between the vortex diameter along the draft tube captured by both cameras, two types of fluctuations related to two different behaviors are distinguished. The fluctuations at f_{UPL} correspond to the real pulsations of the cavitation volume whereas the fluctuations at f_{UPL} + $2f_{PVC}$ (with f_{PVC} the vortex precession frequency) are linked to the elliptical shape of the vortex cross-section. It was demonstrated that the cavitation volume fluctuates with opposite phase from either side of a pressure node located along the cavitation vortex: the total cavitation volume may therefore be equal to zero, contrary to what is observed during full load self-excited instability.

In addition, it was demonstrated that the elliptical shape of the vortex gets more pronounced as the vortex radial position gets closer to the wall far downstream of the runner outlet. This result may be a partial evidence that the elliptical shape is induced by the radial pressure gradient near the wall, and not a proper mode of the cavitation vortex as sometimes suggested in the literature.

３． 共同研究者

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Mohammad Hossein Khozaei (PhD student, Department of Applied Mechanics)

４． 研究業績

4.1 学術論文

[1] M. Khozaei, A. Favrel, T. Masuko, N. Yamaguchi and K. Miyagawa (2021), *Generation of twin vortex rope in the draft-tube elbow of a Francis turbine during deep part-load operation,* ASME Journal of Fluids Engineering, accepted for publication (in press)

[2] J. Decaix, A. Müller, A. Favrel, F. Avellan and C. Münch (2021), *Investigation of the Time Resolution Set Up Used to Compute the Full Load Vortex Rope in a Francis Turbine*, Applied Sciences 11(3):1168

[3] A. Favrel, Z. Liu, M. Khozaei, T. Irie and K. Miyagawa (2021), *Transition of a cavitation vortex rope from cylindrical to elliptical mode in Francis turbine draft tube,* 11th International Symposium on Cavitation

[4] A. Favrel, E. Vagnoni, J. Gomes, A. Müller, M. Sakamoto, K. Yamaishi, F. Avellan and K. Miyagawa (2021), *Dynamic behavior of a full-load cavitation vortex in a Francis turbine draft tube excited at its eigenfrequencies*, 30th IAHR Symposium on Hydraulic Machinery and Systems

[5] A. Amini, E. Vagnoni, A. Favrel, K. Yamaishi, A. Müller and F. Avellan (2021), *An experimental study on the upper part-load elliptical vortex instability in a Francis turbine*, 30th IAHR Symposium on Hydraulic Machinery and Systems

[6] M. Khozaei, A. Favrel, T. Masuko, N. Yamaguchi, R. Watanabe and K. Miyagawa (2021), *Numerical and experimental analysis of pressure fluctuations in the draft-tube of a Francis turbine using the swirl number*, 30th IAHR Symposium on Hydraulic Machinery and Systems

[7] Z. Liu, A. Favrel, W. Takahashi and K. Miyagawa (2021), *Numerical simulation of the unsteady cavitating flow in a Francis turbine draft tube at Upper-Part-Load (UPL) conditions,* 30th IAHR Symposium on Hydraulic Machinery and Systems

[8] A. Favrel, Z. Liu and K. Miyagawa (2020), *Enhancing effect of an open pipe exit on the precessing vortex core occurring in confined swirling flows*, Experiments in Fluids 61(10):211

4.2 総説・著書

4.3 招待講演

4.4 受賞・表彰

4.5 学会および社会的活動

- Member of the ISROMAC18 organizing and scientific committee
- Guest Editor of the ISROMAC18 Special Issue “Aeroacoustics of turbomachines” in Acoustics (MDPI)
- Guest Editor of the ISROMAC18 Special Issue in ASME Journal of Fluids Engineering
- Guest Editor of the Special Issue “Fluid Mechanics in Hydraulic Turbines” in Applied Sciences (MDPI)

５． 研究活動の課題と展望

The draft tube geometry determined by applying an original DOE-ANOM approach will be validated by reduced scale model tests in laboratory and then installed on the full-size machine. The proposed methodology may be extended to other small hydropower projects for further considerations of the impact of off-design operations and may represent an important milestone for the extension of Francis turbine operating range. In addition, the development of active flow control by air injection will be investigated on a simplified test-case reproducing draft tube flow instabilities [8]. A system of axial air injection at the center of the draft tube will be designed and empirically optimized on the simplified test-case for a wide range of operating conditions. The flow mechanisms responsible for the mitigation of the helical precessing vortex in the optimized configuration will be further investigated by means of unsteady CFD simulations. The new findings will be then applied to the reduced scale model of a Francis turbine for validation of the concept.